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## **Space Manufacturing: The Next Great Challenge'**

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## **Space Manufacturing - The Next Great Challenge**

Webster defines manufacturing as “to make by hand or by machinery, often on large scale and with division of labor.” Quite a simple definition when dealing in the gravity-friendly earth environment, and when working within the “comfort zone” of familiar and conventional technologies. It is an all together more complex issue when it must encompass the manufacture of items in the microgravity and vacuum conditions of space. Still, space manufacturing is yet much broader in scope. It encompasses the research, development and manufacture necessary for the production of any product to be used in near zero gravity and vacuum conditions, as well as production of spacecraft required for transporting research or production devices to space. Thus, fabrication of space vehicles, engines, advanced materials, process development, material manufacture, and associated research to support these tasks, as well as commercialization of products falls within this definition.

Manufacturing for space, and manufacturing in space will require significant breakthroughs in materials and manufacturing technology, as well as in equipment designs. Economically, unprecedented cooperation among leading nations, and industries and governments will be necessary to finance such an ambitious undertaking. In the following pages the reader will be made aware of some of the current initiatives embracing this next great challenge.

### **Materials Processing in Space**

The National Aeronautics and Space Administration (NASA) and the microgravity research community's interest in the materials processing in reduced gravity began in the late 1960's with planning for the Skylab orbital space station. Early experiments focused on welding, brazing, and solidification processes that might be utilized for the assembly of large space structures in orbit. Since then a new field of research has developed for the systematic scientific study of materials processes in low gravity. Low gravity (0.01 to 0.0001 times normal Earth gravity) has been obtained utilizing parabolic aircraft flight, drop facilities, and sounding rockets. Microgravity conditions, for extended periods, can be provided by access to near Earth orbit. The emphasis over the last two decades has been on fundamental scientific data that can only be obtained in microgravity, and applying this new knowledge to improving industrially important materials processes on Earth.

With the recent landing of STS-87 NASA is bringing to a close a long and successful Spacelab series of microgravity laboratory missions. The science return from these missions has been quite rich foretelling an abundant science return for the International Space Station. On STS-87 flew the United States Microgravity Payloads forth mission, USMP-4, which was just one of a number of Spacelab mission series, but one that serves as an example of productive scientific research in space. USMP-4 was an effective combination of radio, or teleoperation, controlled experiments and Shuttle Crew operated

experiments that together delivered world class science. The USMP-4 results could well affect the design of future jet engines and computer chips. The immediate products from USMP-4 included unique data, only obtainable from the microgravity environment of space, that can help improve mathematical models and theories that are used in the foundries and crystal growth facilities that produce products that improve our quality of life. Another important element of this mission was the inclusion of numerous experiments from students. The opportunity afforded to these students gives them unique knowledge and insight; knowledge they will eventually carry to the industries of the future. The students interacting with the mission included those in grade school who toured our Payload Operations Control Center at MSFC, and over 30 undergraduate students that helped man the Rensselaer Polytechnic Institute Control Center which controlled dendritic growth experiments on the orbiting Space Shuttle from their campus in Troy, New York. Most important, in the near term, were the numerous graduate students whose research contribution during the mission will contribute to Masters and Ph.D. science degrees which will propel them into high technological careers. During this 16 day mission a number of firsts were accomplished. Metal alloys often solidifying with dendritic, tree or snowflake like, structure at the solid liquid interface. This structure often defines an alloys strength. USMP-4 results included for certain model dendrites the fastest growth and highest undercooling growth ever recorded. A low temperature physics experiment designed to provide data applicable for future generations of computer chips recorded the most precise temperature measurements ever taken in space. While scientists controlled these precision experiments from the ground the crew was busy doing hands on glovebox experiments on the orbiter. During the Particle Pushing Experiment the crew observed the first pushing of large particle clusters or agglomerates by a solidification interface, and differences in flame stability and alloy wetting from that on earth. These results are of interest to the design of jet engines, composites, to cryobiotechnology, and even to road construction. This research, and that of the other Spacelab missions, have produced numerous concepts for pursuit on the International Space Station.

Current proposals for developing an extended human presence, beyond space stations, on the Moon and Mars increasingly consider the processing of non-terrestrial materials essential for keeping the Earth launch burden reasonable. Utilization of in-situ resources for construction of lunar and Mars bases will initially require assessment of resource availability followed by the development of economically acceptable and technically feasible extractive processes. In regard to metals processing and fabrication, the lower gravity level on the Moon (0.125 g) and Mars (0.367 g) will dramatically change the presently accepted hierarchy of materials in terms of physical properties, a factor which must be understood and exploited. Furthermore, significant changes are expected in the behavior of liquid metals during processing. In metal casting, for example, mold filling and associated solidification processes have to be reevaluated. Finally microstructural development and therefore material properties, presently being documented through ongoing research in microgravity science and applications, needs to be understood and scaled to the reduced gravity environments. One of the most important elements of a human planetary base is power production. Lunar samples and geophysical

measurements returned by the Apollo missions provide detailed data on the composition and physical characteristics of the lunar materials and environment. Based on this knowledge and extrapolations of terrestrial industrial experience it is clear that several types of solar-to-electric converters can be manufactured on the Moon. It is conceivable that well over 90% of a solar-to-electric power system could be made from lunar materials. Thus materials processing issues will be quite critical to the establishment of a permanent human presence on the Moon and Mars in an economically feasible manner.

### **Structures Processing in Space**

The adaptation of conventional technologies to operate within the microgravity and vacuum conditions of space will also play a significant role in space manufacturing. In cooperation with the E.O. Paton Electric Welding Institute of the Ukraine, researchers from NASA's Marshall Space Flight Center designed the International Space Welding Experiment (ISWE) to demonstrate welding technology in near-zero gravity. When flown in the Space Shuttle, this flight experiment will assess the applicability of the Ukrainian Universal Hand Tool (UHT) to materials and configurations typical of U.S. space design. Scenarios to be investigated include maintenance and repair, surface coating, cutting, and joining. These tests will provide data allowing space systems designers to expand their options for in-space construction and maintenance. ISWE is only one more step in the development process of space manufacturing. In order for welding to be considered a viable manufacturing technology in the space environment, the process must be demonstrated as capable of satisfying the design requirements of space hardware. To further evolve welding for construction and assembly operations other processing steps must be developed. These include repair, assembly, surface preparation and fit-up of the weld joints; all very complex and difficult tasks to master in the space environment. Postweld quality inspection requirements add to the complexity of the welding operations. The high level of quality required from these operations increases the complexity of these operations in the space environments of vacuum, light-dark orbits, and thermal gradients. Welding, like many other manual operation that may be performed in space, is restricted by space suits and astronaut safety considerations. Use of robotic manipulators will provide the flexibility required for widely varied tasks. New techniques for assembly and inspection of welded structures will need to be developed as space welding matures. The International Space Welding experiment is another step towards the development of space welding as a tool available to future planetary and space habitation endeavors of the world.

### **Earth-based Systems**

A little closer to home, advancements in earth-based manufacturing technologies are key enabling factors paramount to the success of manufacturing in near zero gravity and vacuum conditions of space. First, reliable and low cost launch technology is required to transport manufacturing equipment, personnel and products to and from space. Once

these resources are in space, assets such as the International Space Station can be utilized as a building block orbiting research laboratory and model factory to demonstrate the feasibility of manufacturing by using scaled processes.

To achieve low cost access to space, high performance, lightweight materials are ever increasingly being incorporated in the design and manufacture of space transportation systems. Recent emphasis has been on developing lightweight materials having high specific strength, with the goal of reducing the weight of structures and propulsion systems. Low cost processing technologies are also being pursued to reduce the overall cost of aerospace hardware. Tremendous advances have been made in composite materials and processes in recent years. The variety and availability of materials has improved to the point where designers are no longer constrained by choice of materials so much as in years past. Commensurate developments have improved the options available for automated manufacturing of composites, yet the automated processes remain a more costly option due to the expense of the equipment. These developments over time continue to shift the focus of composite manufacturing to reducing the cost of producing reliable composite hardware, while maintaining high performance. Recent developments in high performance resin systems and manufacturing have paved the road for significant advances in the field of polymer composites. These new polymers exhibit excellent mechanical and thermal properties, toughness, compatibility with chemical and fuels (including cryogenic materials), corrosion resistance, and for space applications, provide protection against atomic oxygen degradation. Improvements in 3-D reinforcement construction, tooling materials, resin transfer processes, and non-autoclave cure methods all have demonstrated potential for bridging the gap between less expensive, low performance composites, and high end automated fabrication, autoclave cured composites. While these recent developments cannot be expected to replace the high performance composites for the most demanding applications, they do expand the list of options from which designers can choose.

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<sup>1</sup> This paper makes extensive use of information previously published by Russell, Carolyn and Paton, Boris in the paper *Space Welding: On The Agenda*.